GLUON RADIATION IN TOP PRODUCTION AND DECAY[a]

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We present the results of an exact calculation of gluon radiation in top production and decay at high energy electron-positron colliders. We include all spin correlations and interferences, the bottom quark mass, and finite top width effects in the matrix element calculation. We study properties of the radiated gluons and implications for top mass measurement.

1 Monte Carlo Calculation

A high energy linear electron-positron collider will provide an excellent environment for producing and studying the top quark, free of the large QCD backgrounds produced in hadron colliders. An important QCD effect which does occur at e^+e^- colliders, however, is the radiation of gluons from the produced top quark and/or its decay products. Radiated gluons appear as additional jets in top events which can complicate event identification and top mass reconstruction.

In this talk we examine gluon radiation in the production and decay ($t \to Wb$) of top quark pairs at high energies[1]; see also[2]. At lepton colliders, there is no gluon radiation from the initial state, but the top quarks and their daughter b quarks can emit gluons.[b] We perform a Monte Carlo calculation of the process

$$e^+e^- \to \gamma^*, Z^* \to t\bar{t}(g) \to bW^+\bar{b}W^-g \ . \tag{1}$$

We compute exact matrix elements of the contributing diagrams with all spin correlations and the bottom mass included. We keep the finite top width Γ_t in the top quark propagator and include all interferences between diagrams, and we use exact kinematics in all parts of the calculation.

Radiation from the top quarks can occur as part of the top production process (before the top quarks go on shell) or as part of the decay process (after the top go on shell). Radiation from the b quarks is always part of top decay. For reconstructing the top quark mass (to identify top events and to measure m_t), whether to include the gluon in the reconstruction is determined by whether the radiated gluon is part of the production or decay process. If it is emitted in the production stage, we obtain the top mass from the W and b momenta only ($m_t^2 = p_{Wb}^2$), but if it is part of the decay, we must include it in the reconstruction ($m_t^2 = p_{Wbg}^2$).

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[b]We neglect radiation from decay products of the W bosons.

In practice this distinction cannot be made absolutely in an experiment, but it is useful to make it in the calculation. There is a single Feynman diagram that contributes to both production- and decay- stage radiation from the top quark, and the corresponding matrix element contains two propagators:

$$ME \propto \left(\frac{1}{p_{Wbg}^2 - m_t^2 + im_t\Gamma_t} \right) \left(\frac{1}{p_{Wb}^2 - m_t^2 + im_t\Gamma_t} \right) \; . \tag{2}$$

We can rewrite the product as

$$\frac{1}{2p_{Wb} * p_{Wbg}} \left(\frac{1}{p_{Wb}^2 - m_t^2 + im_t\Gamma_t} - \frac{1}{p_{Wbg}^2 - m_t^2 + im_t\Gamma_t} \right) \; , \tag{3}$$

which separates the production and decay contributions according to where the terms in parentheses peak. The cross section in turn contains separate production and decay contributions.[c]

2 Results

We show in Figure 1 the fraction of the total cross section due to production stage emission, in events with an extra gluon, as a function of the minimum gluon energy. The solid histogram is for center of mass energy 1 TeV, and the dashed histogram for 500 GeV. The main effect is due to kinematics — both curves fall off with increasing gluon energy because of a reduction in the phase space for gluon emission, and the production fraction is always smaller for the lower collision energy. In both cases decay-stage radiaion dominates for all gluon energy thresholds.

We now consider mass reconstruction. Figure 2 shows top invariant mass distributions with and without the extra gluon included. In both cases there is a clear peak at the correct value of m_t. In the left-hand plot, where the gluon is not included in the reconstruction, we see a low-side tail due to events where the gluon was radiated in the decay. Similarly, in the right-hand plot we see a high-side tail due to events where the gluon was radiated in association with production, and was included when it should not have been.

The narrowness of the peaks and the length of the tails in Figure 2 suggests that an invariant mass cut would be useful to separate the two types of events. We can in fact do even better using cuts on the angle between the gluon and the b quarks. This works because although there is no collinear singularity

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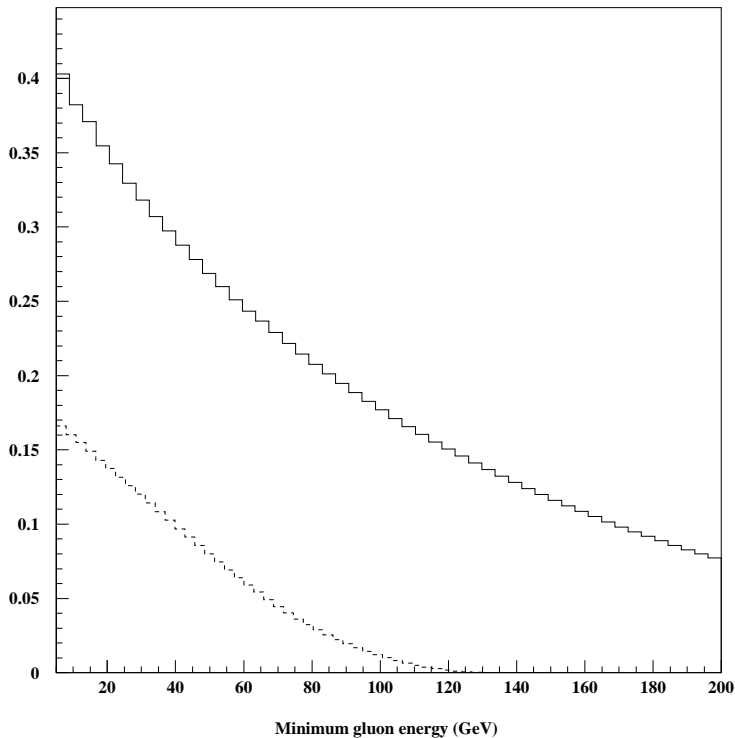[c]It also contains interference terms, which in principle confound the separation but in practice are small.

Figure 1: The fraction of gluon emissions radiated in the production stage, as a function of minimu gluon energy, for center-of-mass energy 1 TeV (solid line) and 500 GeV (dashed line).

for radiation from massive quarks, the distribution of gluons radiated from b quarks peaks close to the b direction. Such gluons are emitted in decays. We should note that an important reason the cuts are so effective is that we work at the parton level. In an experiment, hadronization and detector effects are likely to significantly reduce the resolution.

Finally we turn to the interference between the production- and decay-stage radiation, which though small is interesting for its sensitivity to the top width Γ_t (about 1.5 GeV in the Standard Model).[3] The interference between the two propagators shown above can be thought of as giving rise to two overlapping Breit-Wigner resonances. The peaks are separated roughly by the gluon energy, and each curve has width Γ_t. Therefore when the gluon energy becomes comparable to the top width, the two Breit-Wigners overlap and interference can be substantial. In constrast, if the gluon energy is much larger than Γ_t, overlap and hence interference is negligible. Hence the amount of interference serves as a measure of the top width.

This effect was discussed in [3] using the soft gluon approximation, and Figure 3 shows that the effect remains in the exact calculation. There we plot the distribution in the angle between the emitted gluon and the top quark for gluon energies between 5 and 10 GeV and with $\cos\theta_{tb} < 0.9$. The center-of-mass energy is 750 GeV. The histograms show the decomposition into the
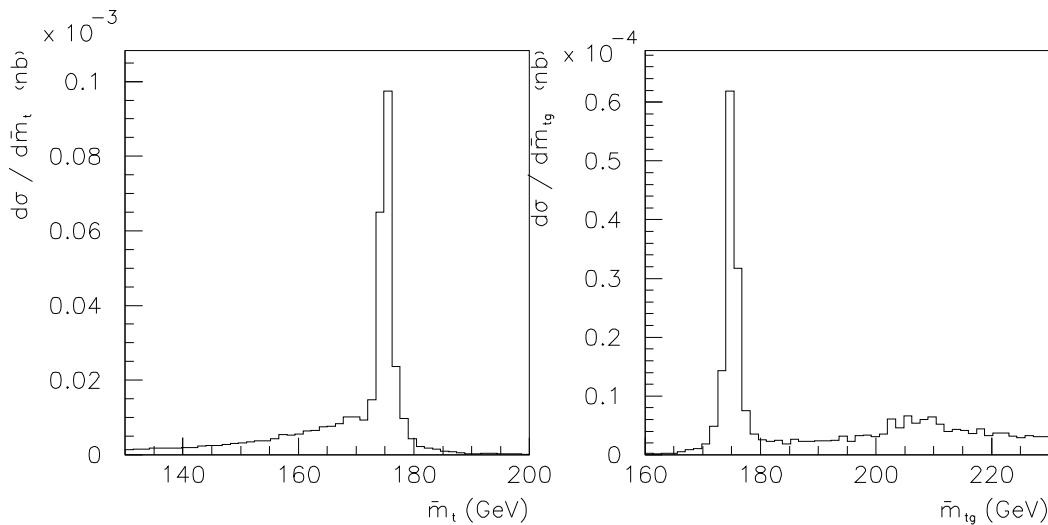
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Figure 2: The top invariant mass spectrum without (left) and with (right) the gluon momentum included, for center-of-mass energy 600 GeV.

various contributions. The negative solid histogram is the production-decay interference, and we see that not only is it substantial, it is also destructive. That means that the interference serves to suppress the cross section. If the top width is increased, the interference is larger, further suppressing the cross section. Although the sensitivity does not suggest a precision measurement, it is worth noting that the top width is difficult to measure by any means, and it is the total width that appears here.

In summary, we have presented preliminary results from an exact parton-level calculation of real gluon radiation in top production and decay at lepton colliders, with the b quark mass and finite top width, as well as all spin correlations and interferences included. We have indicated some of the issues associated with this gluon radiation in top mass reconstruction and top width sensitivity in the gluon distribution. Further work is in progress.

Acknowledgments

References

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3. V. Khoze, L.H. Orr and W.J. Stirling, Nucl. Phys. **B378** 413 (1992).
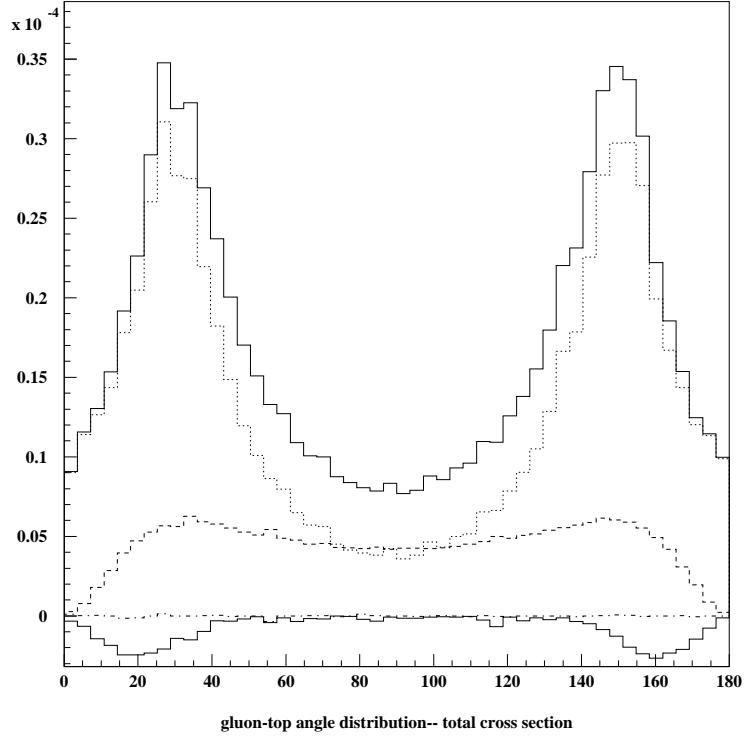
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gluon-top angle distribution-- total cross section

Figure 3: The distribution in angle between the top quark and the gluon for gluon energies from 5 to 10 GeV, $\cos\theta_{tb} < 0.9$, and 750 GeV collision energy. The upper solid histogram is the total and the other histograms represent the individual contributions: dotted: decay; dashed: production; dot-dashed: decay-decay interference; solid: production-decay interference.